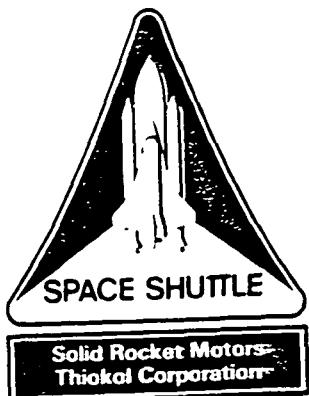


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P 44

TWR-60187



Follow-on Cable Coupling Lightning Test Final Test Report

Volume I

31 October 1990

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Contract No. NAS8-30490
DR No. 5-3
WBS No. 4B102-11-10
ECS No. SS3900

Thiokol CORPORATION
SPACE OPERATIONS

PO Box 707, Brigham City, UT 84302-0707 (801) 863-3511

Publications No. 91230

(NASA-CR-184123) FOLLOW-ON CABLE COUPLING
LIGHTNING TEST, VOLUME 1, Final Test Report
(Thiokol Corp.), 43 p

N91-28192
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**Follow-on Cable Coupling Lightning Test
Final Test Report**

Volume I

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ABSTRACT

From 1 May to 8 June 1990 at Thiokol Corporation Lightning Test Complex in Wendover, Utah, Thiokol and United Space Boosters Inc. subjected a redesigned solid rocket motor test article to simulated lightning strikes. As part of an ongoing lightning strike test program, this test was performed to evaluate the effects of a lightning strike to the redesigned solid rocket motor and Space Transportation System. The purpose of the testing sequence was to evaluate the performance of systems tunnel design changes when subjected to the lightning discharges. The goal of the design changes was to reduce lightning-induced coupling to cables within the systems tunnel.

The test article was subjected to 56 Marx generator discharges, 46 high-current bank discharges, and 8 combination high-current and continuing-current bank discharges. Coupling levels detected during the Marx test to the systems tunnel were reduced between 6 and 36 decibels. High current bank levels were still high, ranging from 2.9 to 68.5 amperes. The dominant mode of coupling appears to be caused by the diffusion of the magnetic fields through the systems tunnel covers.

The results from bond strap integrity testing showed that 16 of 18 bond straps survived. Nine survived an action integral of two million ampere squared seconds; four survived an action integral of four million ampere squared seconds. Testing showed that TRADUCT 2902 is a better bonding agent than ECCOBOND 56C.

Design change evaluations showed that coupling reduction ranged from 0 to 36 decibels for each type of cable. The type of cable has less effect on coupling than does strike location and strike levels.

It is recommended that TRADUCT 2902 replace ECCOBOND 56C as the conductive bonding agent. It is also recommended that the current method of ground equipment instrumentation cable shielding be continued. Further, it is recommended that data from this test and other similar tests be used to determine the feasibility of successfully modifying the systems tunnel to reduce coupling.

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INTRODUCTION

This report documents the procedures, performance, and results obtained from the evaluation of simulated lightning discharges to a redesigned solid rocket motor (RSRM) test article. The test was conducted following WTP-0238 which incorporated United Space Boosters Inc. (USBI) test plan SYS-10-PLAN-004 and complied with JSC 20007 and NSTS 07636, Rev D.

The purpose of this series of tests was to determine the lightning induced coupling in operational flight (OF) cables following bond strap and cover bond strap design changes; to evaluate six designs of systems tunnel cover-to-case external bond straps; and to determine the optimal systems tunnel external bond strap design that is most likely to survive the simulated lightning discharge requirements of NSTS 07636, Rev D. This test was accomplished by applying simulated lightning discharges onto an RSRM case, systems tunnel, and external sensor cable shields, and then evaluating the measured open-circuit voltage and short-circuit current induced on the OF cables within the systems tunnel. In addition, survivability of the systems tunnel cover-to-case external bond straps were evaluated using high-current discharges.

Electro-Magnetic Applications, Inc. (EMA) acted as subcontractor to Thiokol Corporation providing analytical support and assistance in test site operation. EMA's test report EMA-90-R-40 is a source of information for this report and is included in the Appendix. This report contains the primary results of the EMA document.

1.1 TEST ARTICLE DESCRIPTION

The test article configuration was controlled by Thiokol's Drawing 7U77268 and USBI's Drawing 90001-0050. Any other flight components not included in that description had no effect on the results.

The coupling test utilized the following configurations:

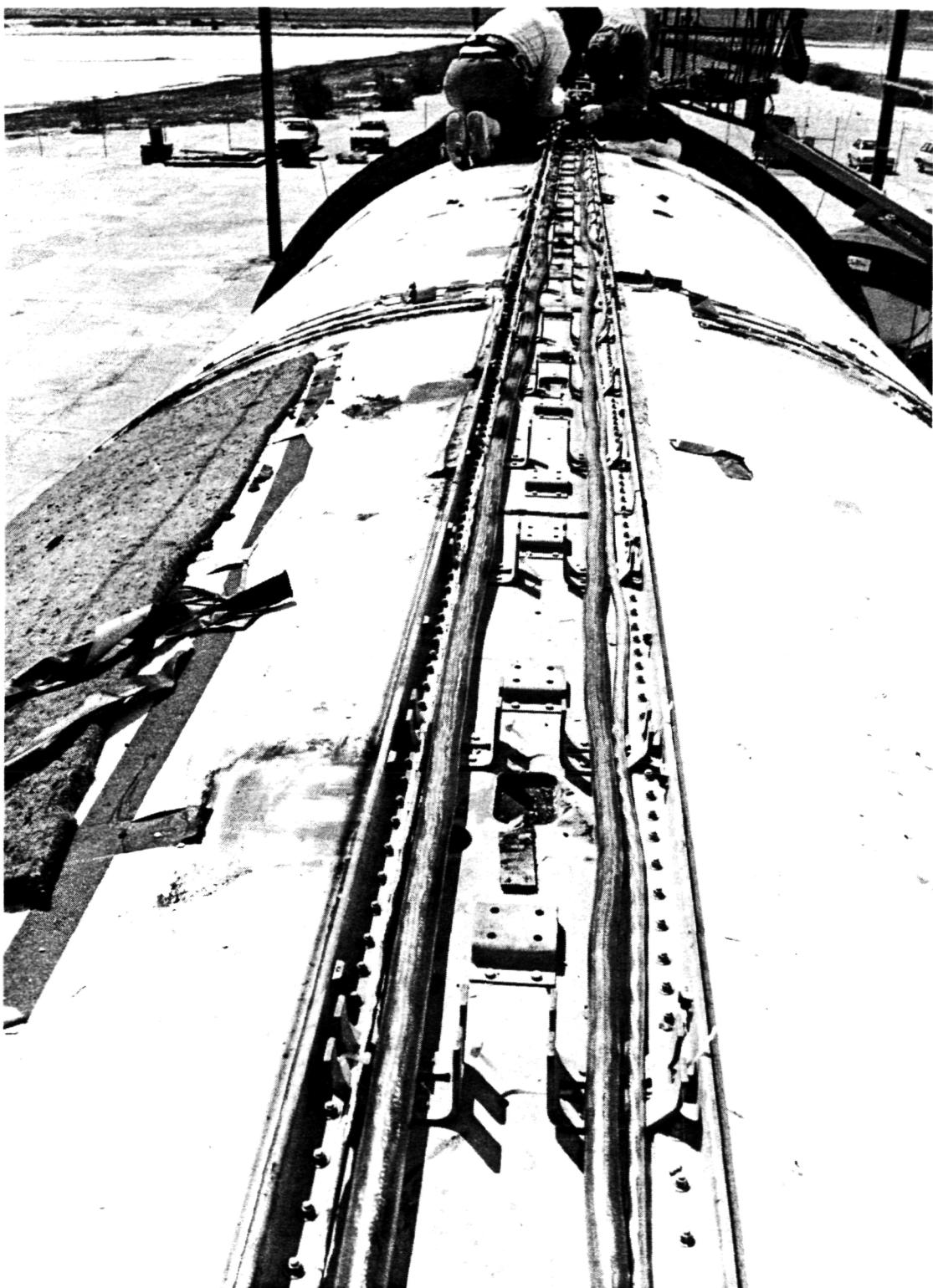
- Flight Configuration (baseline configuration)
- Flight Configuration (new bonding agent)
- Modified Configuration (external bond straps installed)
- Modified Configuration (external ground equipment instrumentation (GEI) and heater cables removed)

1.1.1 Flight Configuration (baseline design)

The test article consisted of forward and aft mated RSRM segments, flight nozzle, flight aft dome, flight exit cone, flight floor plates (including bond straps), and instrumentation (GEI) cables. Systems tunnel configuration and systems tunnel bonding met flight configuration. The OF and GEI cables were routed through an aluminum systems tunnel to simulate flight configuration of the cables (Figure 1). Instrumentation cables were installed per flight procedures using ECCOBOND 56C (STW4-2874) with the exception that each temperature sensor was replaced by a resistor that represented the characteristic impedance of the temperature sensor it replaced. The cables on the exterior surface were configured to simulate flight configuration but without the thermal protection systems (TPS). The RSRM current exit point was located at the aft case forward of the nozzle.

1.1.2 Flight Configuration (new bonding agent)

The test article was assembled in the same configuration as described in Para 1.1.1 except that the instrument cables were installed using TRADUCT 2902 (STW4-3766).



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Figure 1. OF and GEI Cables on Systems Tunnel

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1.1.3 Modified Configuration (external bond straps installed)

The test article was assembled in the same configuration as described in Para 1.1.1 except for the addition of the USBI proposed hardware changes (controlled by Drawing 90001-0050 and Test Plan SYS-10-PLAN-004) intended to reduce induced coupling in the OF and GEI cables within the systems tunnel. The changes are summarized below.

- a. Replaced existing systems tunnel cover-to-cover bonding straps with a new design.
- b. Replaced current RSRM flight configuration internal systems tunnel bonding straps with straps from each new design systems tunnel cover-to-case external bonding straps (18 total straps).
- c. Bonded all external cable shields at their systems tunnel entry and along their length as per flight configuration.

1.1.4 Modified Configuration (external GEI and heater cables removed)

This configuration was the same as described in Para 1.1.1 except for the following.

- a. All external GEI and heater cables were removed.
 1. All external cables entering the systems tunnel were removed and a space of at least 2 feet was maintained between cable ends and the sides of the systems tunnel.
 2. Heater cables were removed at the external tank (ET) attach ring and the connector at the ET attach ring was covered by an aluminum cap.

1.1.5 Test Article Setup

The test article was placed between two parallel wire grids covering an area of 2,500 square meters. One of the grids was laid out over the ground and the other grid was suspended 9 meters above the first grid (Figure 2). This grid setup

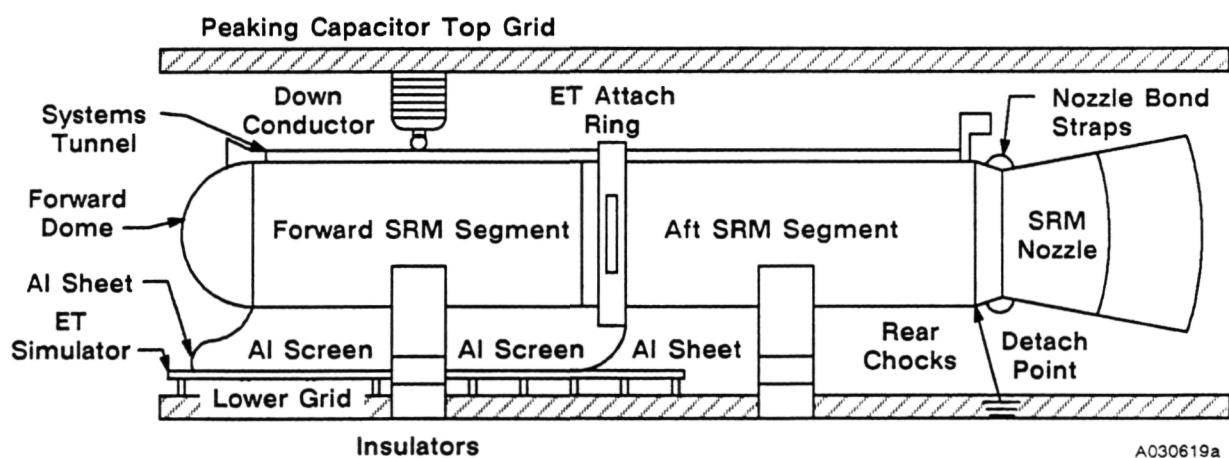


Figure 2. Test Article Configuration

represented the two parallel plates of the 2.5 nano-Farad (nF) peaking capacitor.

The test article was subjected to 56 Marx generator discharges, 46 high-current bank (HCB) discharges, and 8 combination HCB and continuing-current bank (CCB) discharges—a total of 110 discharges.

The 56 Marx generator discharges were made by direct arc attachment to the RSRM case, systems tunnel, and external sensor cable shields. The Marx discharges simulated the fast rise in current with respect to time (di/dt) of a worst-case lightning discharge to unprotected flight hardware on the ground (NSTS 07636, Rev D).

The 46 simulated lightning discharges from the HCB were made by direct arc attachment to the RSRM case, systems tunnel, and external cable shield. The HCB simulated the peak current of a worst-case lightning discharge to unprotected flight hardware on the ground (NSTS 07636, Rev D).

The eight HCB/CCB combined discharges were by direct arc attachment to the RSRM case and systems tunnel. The combined discharge simulated the peak and sustained current of a worst-case lightning discharge to unprotected flight hardware on the ground (NSTS 07636, Rev D).

1.2 PREVIOUS TESTING

In 1989 Thiokol, in conjunction with USBI and EMA, conducted a series of lightning strike tests intended to demonstrate the level of coupling that OF cables would experience. Prior testing and analysis showed that these levels would be very low. However, the results of CTP-0051 testing (in 1989) indicated that a very high level of coupling would result from a lightning strike.

TWR-17796, Rev A, the final report for CTP-0051, recommended further testing to perform the following objectives:

- a. Evaluate methods of improving electrical bonding between individual sections of the systems tunnel covers.
- b. Investigate methods of shielding the instrumentation sensors from the direct effects of a lightning strike.
- c. Provide better characterization of RSRM cable coupling effects as an aid in developing methods to reduce coupling levels.
- d. Continue deviations to NASA lightning specification NSTS 07636 for the indirect effects of a lightning strike on the GEI and OF cables until methods of reducing coupling levels to cables within the systems tunnel can be developed and evaluated.

OBJECTIVES

The following test objectives of WTP-0238 were derived from the recommendations of TWR-17796, Rev A:

- A. Determine the magnitude and level of reduction in cable coupling to OF cables in the systems tunnel.
- B. Evaluate the lightning discharge survivability of the six proposed systems tunnel cover-to-case external bond strap designs.
- C. Evaluate design changes intended to reduce induced open circuit voltage in the OF cables to the safety margins of 20 decibels (dB) for all ordnance functions and 6 dB for all other functions.

EXECUTIVE SUMMARY

3.1 SUMMARY

This section contains an executive summary of the key results from test data evaluation and post-test inspection. Additional information and details can be found in Section 6, Results and Discussion.

3.2 CONCLUSIONS

The following are test objectives and corresponding conclusions. Additional information about the conclusions are in Section 6, Results and Discussion.

<u>Objectives</u>	<u>Conclusions</u>
A. Determine the magnitude and level of reduction in cable coupling levels.	<i>Determined.</i> Coupling levels detected during the Marx test to the systems tunnel were reduced from between 6 and 36 dB. HCB levels were still high, ranging from 2.9 to 68.5 amperes (amp). It is apparent that the dominant mode of coupling is due to the diffusion of the magnetic fields through the systems tunnel covers.
B. Evaluate the lightning discharge survivability of the six proposed systems tunnel cover-to-case external bond strap designs.	<i>Evaluated.</i> There were 16 of 18 bond straps that survived the integrity test. Nine survived an action integral of 2 million amp squared seconds, four survived an action integral of 4 million amp squared seconds. TRADUCT 2902 was used in the place of ECCOBOND 56C to bond some of the straps to the RSRM case. The results indicate that TRADUCT 2902 is a better bonding agent than ECCOBOND 56C.

Objectives

C. Evaluate design changes intended to reduce open circuit voltage induced into the OF cables by a safety margin of 20 dB for all ordnance functions and 6 dB for all other functions.

Conclusions

Evaluated. Comparing data from this test and previous testing, a reduction in coupling ranges was from 0 to 36 dB on all cables. Type of cable does not seem to have as much of an effect on coupling as does location with respect to strike and peak levels of strike.

3.3 RECOMMENDATIONS

Based on the results of this test, recommendations are as follows:

- a. Since test data showed that TRADUCT 2902 performed better than ECCOBOND 56C, it is recommended that TRADUCT 2902 replace ECCOBOND 56C as the conductive bonding agent on the RSRM.
- b. Since testing showed that the current GEI cable shield helps reduce the effects of a lightning strike, it is recommended that this method of shielding be continued.
- c. Since limited improvement of cable coupling was seen, it is recommended that data from this test and similar tests and analyses should be analyzed in a susceptibility study of all circuits that interface with the cables in the systems tunnel. The results of this study need to be evaluated to determine the feasibility of making modifications to the systems tunnel to reduce cable coupling.

4

INSTRUMENTATION

Instrumentation used during this test is listed in TWR-18364, Lightning Tests Instrumentation Report. All test instruments were electrically zeroed and calibrated in accordance with MIL-STD-45662.

5

PHOTOGRAPHY

Still color photographs were taken of the test article assembly, before and after the simulated lightning discharges. Copies of the photographs (Series 117484, 117572, and 117887) are available from the Thiokol Photographic Services department. Color motion pictures were taken with a documentary and a high-speed camera.

6

RESULTS AND DISCUSSION

6.1 TEST ARTICLE ASSEMBLY

The test article was assembled in accordance with Thiokol's Drawing 7U77268 and USBI's Drawing 90001-0050. Drawing 7U77268 detailed the installation of the GEI cables and the method that was used to bond the external shields of these cables to the case. Drawing 90001-50 detailed the installation of the external bond straps and the cover to cover bond straps. The installation of all components was inspected by Thiokol and USBI engineers prior to testing.

6.2 SWEPT CONTINUOUS WAVE TESTING

Prior to full threat level tests, swept continuous wave (CW) tests were conducted on the modified configuration. Swept CW tests are conducted by subjecting a low-level radio frequency CW signal to the RSRM at the expected attachment point. Then a network analyzer is used to measure the signal that is coupled onto the test cable. The results are expressed as a ratio of input current to detected current and has the unit designation dB. Typical power level of the injected signal is 20 to 50 watts. The purpose of the CW test is to obtain data to be used during the equipment setup before the test and during the data reduction. The results of these tests were compared to the results of the previous test conducted under CTP-0051 on the unmodified configuration. The latest results indicate a large reduction of coupling in the high-frequency range. The low-frequency range showed some slight improvement. These results were verified in the full threat level tests that were conducted on the modified configuration. A more complete description of CW tests and how the results relate to high-level tests is contained in Chapter 2 of EMA-90-R-40.

6.3 SIMULATED LIGHTNING TESTS

The Marx generator HCB and CCB were used to inject 110 simulated lightning strikes to the RSRM case. All test waveforms complied with NSTS 07636, Rev D. The down conductor was positioned in six locations during the cable coupling portion of the tests (Figure 3). These locations were as follows:

Location 1: Systems tunnel centered on the forward tunnel cover.

Location 2: GEI cable located at Station 539 and approximately 9 in. from the systems tunnel.

Location 3: The forward case at the forward skirt attachment ring and approximately 6 in. from the case.

Location 4: Systems tunnel approximately 3 ft from the ET attach ring.

Location 5: GEI cable at Station 1701 approximately 6 in. from the systems tunnel.

Location 6: Heater cable attachment point to the ET attach ring.

During the bond strap test the down-conductor was positioned over the bond strap being test.

6.3.1 Marx Generator

The Marx generator was used to simulate the rapid current rise with respect to time or high di/dt of the lightning strike. The requirement is a di/dt of $1.4 \times 10E11$ amp/sec. The di/dt of the injected signal from the Marx ranged from $1.62 \times 10E11$ down to $0.87 \times 10E11$. The results of the Marx test are consistent with the results of the CW tests, which showed a dramatic reduction in coupling of the high-frequency component of the lightning waveform.

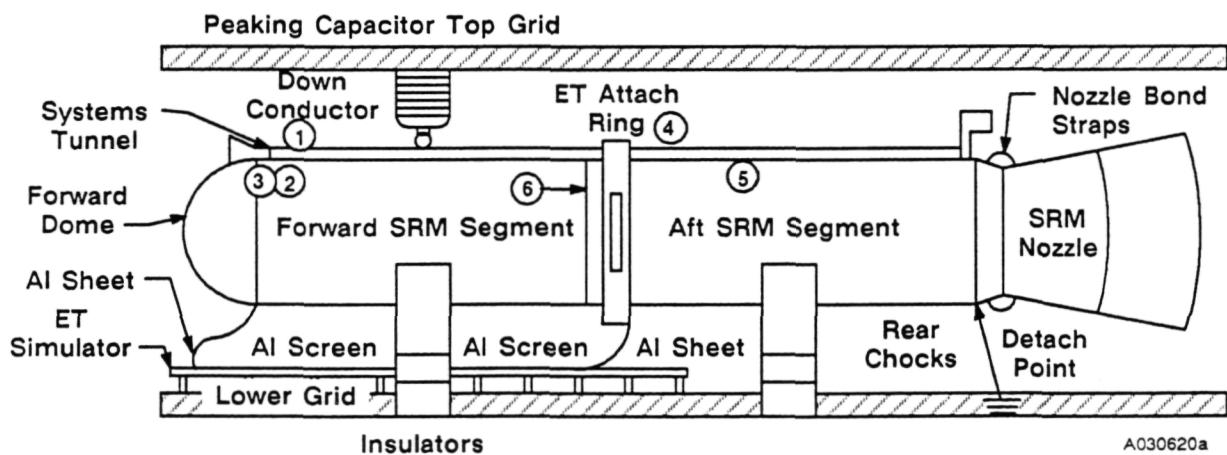


Figure 3. Down Conductor Attachment Locations

6.3.2 High Current Bank

The HCB was used to simulate the worst-case physical effects (burning, blasting, etc.) in addition to generating the large magnetic fields associated with a lightning strike. Injected current and the action integral were measured. The requirements from NSTS 07636, Rev D, are peak currents of 200,00 amp and action integrals of 2 million amp squared seconds. The injected current levels in the cable coupling portion of the tests ranged from 63,000 to 75,000 amp with action integrals of 650,00 to 1.3 million amp squared seconds. The short-circuit current levels that were detected on the cables ranged from 2.9 to 68.5 amp. These levels are scaled to flight levels in Tables 1.5 and 1.6 in EMA-90-R-40.

6.3.3 High Current Bank and Continuing Current Bank

As part of the bond strap evaluation tests, eight tests were conducted by firing the HCB and the CCB concurrently. Because of damage to some of the controlling circuits and the CCB, only a few tests were performed with both banks firing concurrently. After CCB failure, the testing continued with only the HCB. It has been concluded that CCB failure does not affect the results of the testing. In discussion with EMA and USBI representatives, it was demonstrated by mathematical comparison of current bank energies that the HCB delivered better than 99 percent of the destructive energy. Some bond straps were tested to action integrals exceeding requirements and did not fail. This tends to substantiate the use of HCB testing alone.

6.3.4 Baseline Testing

One objectives of the test plan was to determine the amount of improvement that modifications to the systems tunnel bonding would have on the coupling levels. To accomplish this objective, a series of baseline Marx tests were conducted. This baseline configuration was the configuration that is found on a flight article. It consisted of mated forward and aft segments with the systems tunnel and bond

straps installed and bonded per flight conditions. The GEI cables external shields were bonded as per flight conditions according to Drawing 7U77268. The results of these tests are included in Table 1. Cables No. 6, 7, 11, 12 were of utmost interest, and they were the only cables monitored. No HCB shots were performed. The results from this test (Table 2) compared favorably to the results from CTP-0051 testing as shown in Table 3. This demonstrates the repeatability of the data. The CW data from both tests provide an indication of the coupling expected as a result of using the HCB.

Table 1. Comparison With and Without GEI Cable Installed

Cable No.	Injection Point	Shot No. With Cable	Shot No. Without Cable	Marx/ HCB	With Cable (dB)	Without Cable (dB)
6	1	49	67	HCB	-65.27	-66.70
6	3	43	64	HCB	-66.96	-66.92
7	1	51	66	HCB	-70.17	-74.91
7	3	45	65	HCB	-69.18	-70.28
11	1	51	66	HCB	-73.16	-75.33
11	3	45	65	HCB	-77.61	-74.18
12	1	49	67	HCB	-78.41	-80.57
12	3	43	64	HCB	-77.99	-79.05
6	1	9	72	Marx	-103.70	-83.89
6	3	16	75	Marx	-89.45	-86.97
7	3	17	7	Marx	-123.60	-99.22
11	3	17	7	Marx	-98.88	-103.70
12	1	9	72	Marx	-102.10	-98.72
12	3	16	75	Marx	-100.90	-99.43

Table 2. Baseline Test Data

1 Cable No.	2 Shot No.	3 Injection Point	4 Injection I (amp)	5 di/dt (x10E11)	6 Cable I (amp)	7 I/Injection I (dB)	8 Plot No.
6	113	1	31,880	1.28	3.72	-78.66	344
6	114	2	32,700	1.28	2.15	-83.642	348
6	110	3	31,400	1.4	1.89	-84.409	332
7	112	1	30,470	1.28	2.2	-82.829	340
7	111	3	30,730	1.11	1.5	-86.229	336
11	112	1	30,470	1.28	0.6	-94.114	341
11	111	3	30,730	1.11	0.6	-94.188	337
12	113	1	31,880	1.28	0.3	-100.53	345
12	114	2	32,700	1.28	0.2	-104.27	349
12	110	3	31,400	1.4	0.2	-103.92	333

Table 3. Comparison of Continuous Wave Data USBI Retest to CTP-0051

USBI Retest				CTP-0051			
Cable No.	Injection Point	dB (at 5 kHz)	dB (at 100 kHz)	Cable No.	Injection Point	dB (at 5 kHz)	dB (at 100 kHz)
6	1	-63	-108	6	1	-56	-72
6	3	-73	-100	6	3	-63	-75
7	1	-60	-120	7	1	-68	-75
7	3	-73	-120	7	3	-68	-85
8	1	-56	-120	8	1	-55	-77
8	3	-73	-120	8	3	-72	-76
10	1	-73	-120	10	1	-73	-84
10	3	-76	-120	10	3	-73	-108
11	1	-76	-108	11	1	-74	-83
11	3	-74	-120	11	3	-70	-86
12	1	-74	-120	12	1	-65	-85
12	3	-83	-120	12	3	-73	-97

6.3.5 External Cables Removed

One of the testing configurations had all external cables removed from the systems tunnel and the ET attach ring. Cable removal was accomplished by disconnecting all GEI cables at the tunnel entrance and removing the external cables. A minimum of 2-ft spacing between the tunnel and the cable was maintained. The test team also verified that no cables inside the systems tunnel extended from the tunnel to under the floor plate. The heater power cable and sensor cable were disconnected at the ET attach ring, and the external connector on the ET attach ring was covered with an aluminum cap. Short-circuit current levels comparisons are shown in Table 1.

6.3.6 Bond Strap Designs

Five external bond strap designs were tested instead of six designs as called for in WTP-0238. The USBI-proposed sixth design consisted of K5NA cork-filled epoxy ablation compound applied to the bond straps. This was not a bond strap design; rather, it was a bond strap attachment method.

The following five bond strap designs were tested.

- Solid aluminum, 4-in. by 4-in. bond area (Figure 4)
- Solid aluminum, 4-in. by 4-in. bond area with five rows of 1/16-in. holes (Figure 5)
- Solid aluminum, 4-in. by 4-in. bond area with notches cut out around the edges (Figure 6)
- Braided aluminum, 3-in. by 4-in. bond area (Figure 7)
- Braided aluminum, 2-in. by 4-in. bond area (Figure 8)

Cover-to-cover bond straps consisted of a thin strip of aluminum. External and cover-to-cover bond strap locations were controlled by USBI drawing 90001-0050.

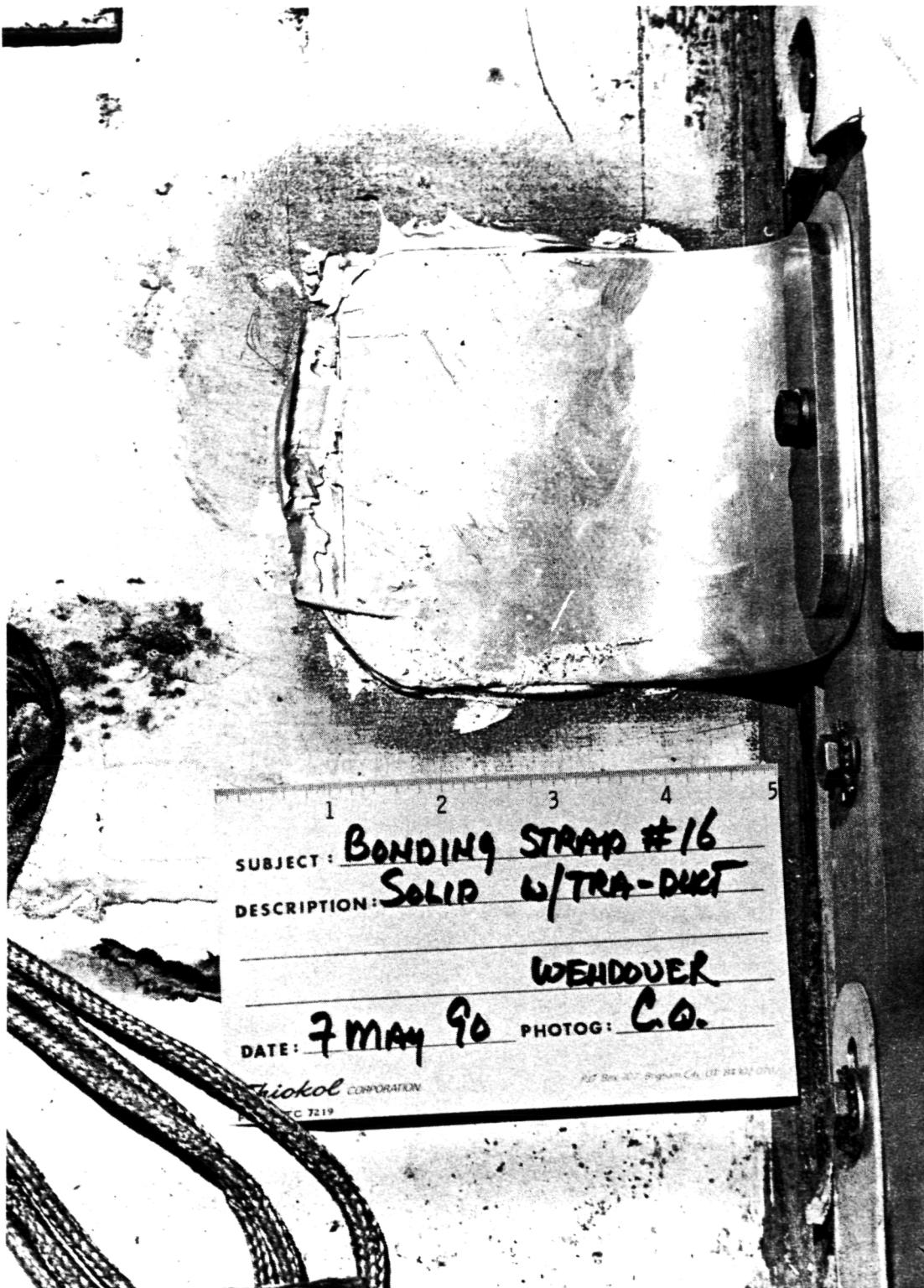


Figure 4. Solid Aluminum Bondline Strap

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Figure 5. Solid Aluminum Bonding Strap With Holes

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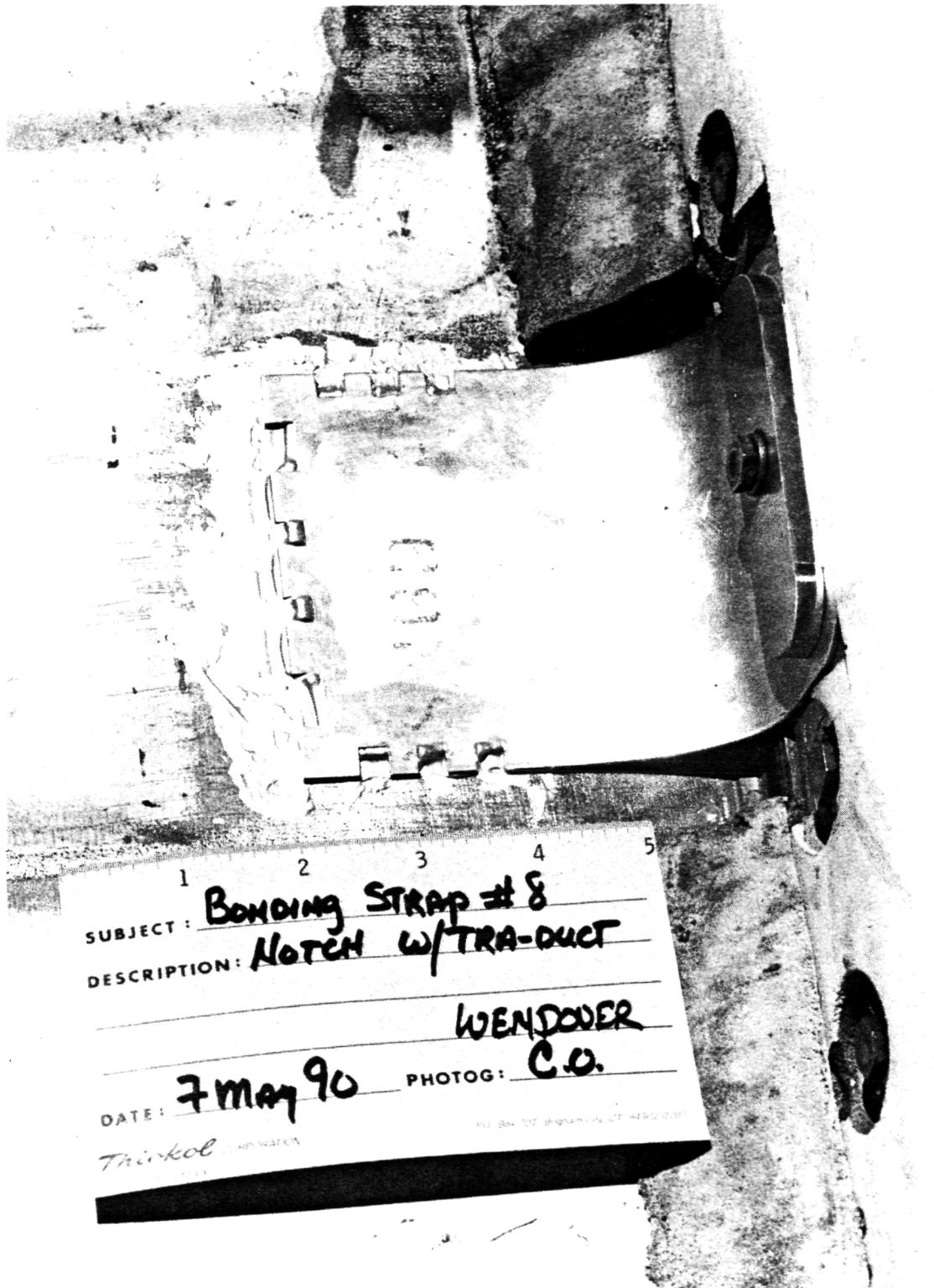


Figure 6. Solid Aluminum Bonding Strap With Notches

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Figure 7. Braided Aluminum Bond Strap (3 in. wide)

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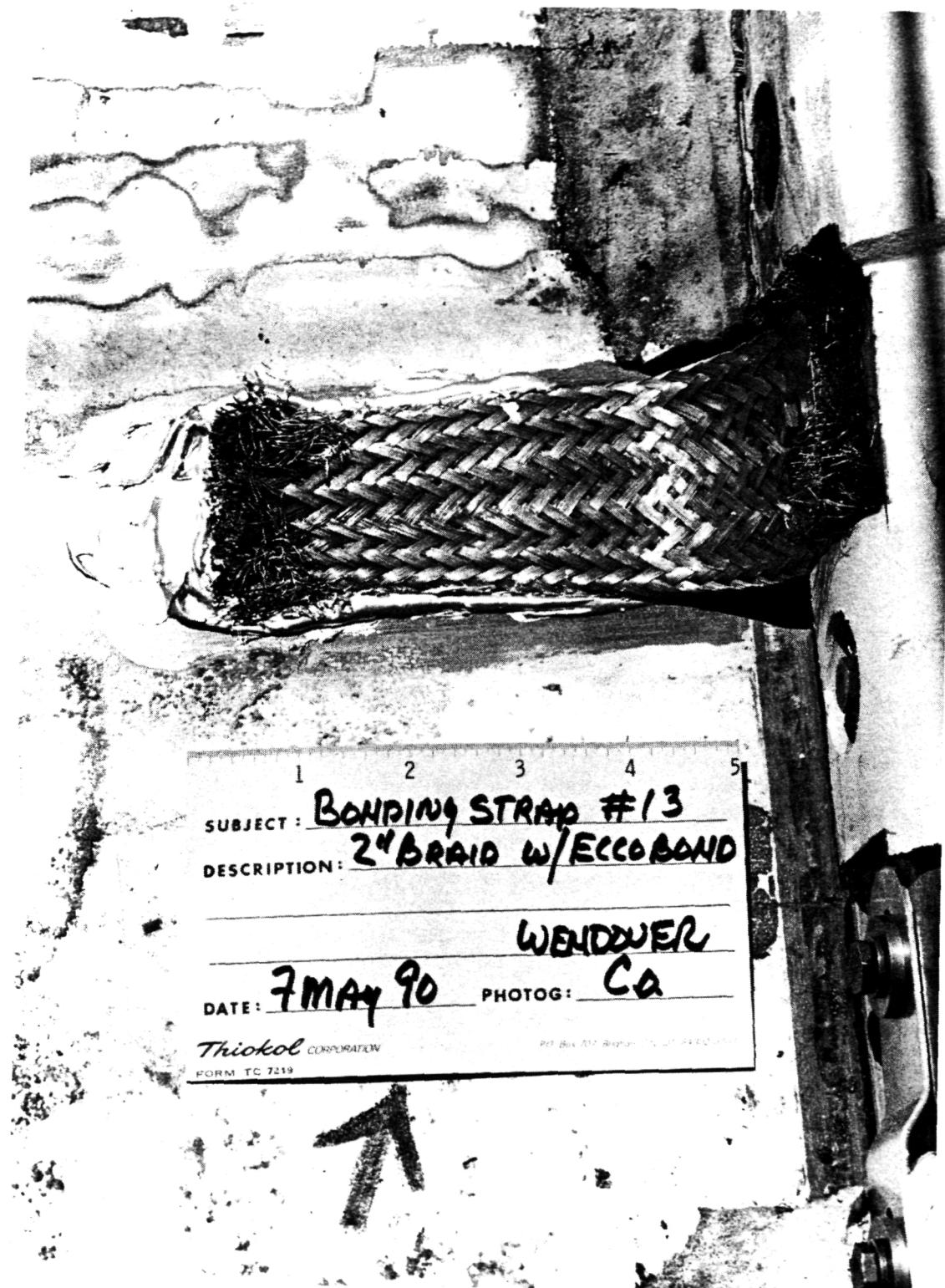


Figure 8. Braided Aluminum Bond Strap (2 in. wide)

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6.3.7 Bond Strap-to-Case Attachment Methods

The following three methods were used to attach bond straps to the case.

- A. ECCOBOND 56C
- B. TRADUCT 2902
- C. K5NA

TRADUCT 2902 (Figure 7) and ECCOBOND 56C (Figure 8) are conductive epoxies and K5NA (Figure 9) is a cork-filled epoxy ablation compound. ECCOBOND 56C is currently used as the conductive adhesive.

The bond strap-to-case attachment methods were controlled by USBI drawing 900010-0050.

6.4 SUMMARY OF RESULTS

Tables 4 and 5 compare the currents that were detected on the OF cables during high-level testing to the injected current levels of the Marx generator testing and HCB testing, respectively. Table 6 compares CW test results to Marx generator

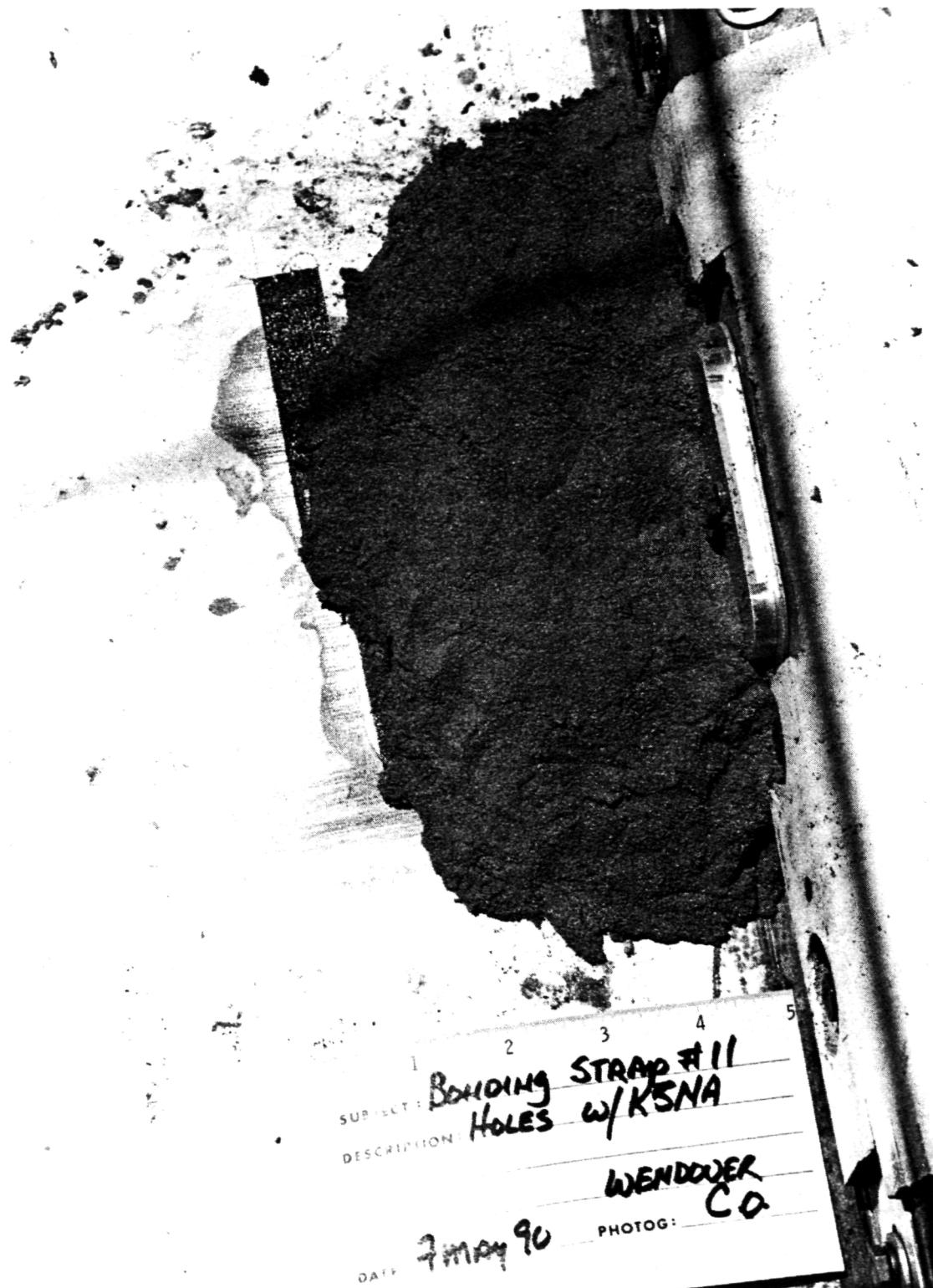


Figure 9. K5NA Cork-Filled Epoxy Ablation Compound

Table 4. Ratio of Marx Injected Current and Current Measured on Cables (dB)

1 Cable No.	2 Shot No.	3 Injection Point	4 Marx I (amp)	5 di/dt (x10E11)	6 Cable I (amp)	7 I/Marx I (dB)
6	9	1	31080	1.33	0.202	-103.74
6	72	1	22570	0.87	1.442	-83.891
6	16	3	27340	1.09	0.9209	-89.452
6	75	3	22480	0.99	1.008	-86.967
6	24	4	21690	1.27	0.03781	-115.17
6	71	4	31080	1.43	0.1763	-104.92
6	32	5	23340	1.118	0.05101	-113.21
6	34	5	22330	1.09	0.07271	-109.75
6	76	6	20980	1.28	0.2178	-99.675
7	10	1	28710	1.62	0.1824	-103.94
7	37	1	23620	1.08	0.3464	-96.674
7	40	2	23840	1.09	0.4094	-95.303
7	17	3	27540	1.28	0.01824	-123.58
7	41	3	22130	1.08	0.354	-95.92
7	74	3	21180	1.06	0.2317	-99.22
7	25	4	22470	1.27	0.01135	-125.93
7	35	4	28480	1.36	0.1111	-108.18
7	70	4	27380	1.41	0.1111	-107.83
7	33	5	23480	1.21	0.0102	-127.24
7	77	6	21160	1.2	0.0669	-110
8	11	1	27830	1.21	0.0556	-113.99
8	18	3	27520	1.1	0.0466	-115.43
8	26	4	21550	1.17	0.1462	-103.37
10	11	1	27830	1.21	0.1781	-103.88
10	18	3	27520	1.1	0.1651	-104.44
10	26	4	21550	1.117	0.1317	-104.28
11	10	1	28710	1.62	0.3314	-98.754
11	37	1	23620	1.08	0.2646	-99.014
11	40	2	23840	1.09	0.2839	-98.483
11	17	3	27540	1.28	0.3133	-98.88
11	41	3	22130	1.08	0.3436	-96.179
11	74	3	21180	1.06	0.1379	-103.73
11	25	4	22470	1.27	0.25	-99.073
11	35	4	28480	1.36	0.1691	-104.53
11	70	4	27380	1.41	1.203	-87.143
11	33	5	23480	1.21	0.2091	-101.01
11	77	6	21160	1.2	0.1228	-104.73
12	9	1	31080	1.33	0.2445	-102.08
12	72	1	22570	0.87	0.261	-98.738
12	16	3	27340	1.09	0.2478	-100.85
12	75	3	22480	0.99	0.24	-99.432
12	24	4	21690	1.27	0.48	-93.1
12	71	4	34080	1.43	2.182	-83.873
12	34	5	22330	1.09	0.3224	-96.81
12	76	6	20980	1.28	0.63	-90.449

Table 5. Ratio of HCB Discharges and Current Measured on Cables (dB)

1 Cable No.	2 Shot No.	3 Injection Point	4 HCB Injection (amp)	5 Cable I (amp)	6 I/Injection I (dB)
6	49	1	66350	36.16	-65.272
6	67	1	75710	35.01	-66.699
6	55	2	64520	33.24	-65.761
6	43	3	77900	34.96	-66.959
6	64	3	73940	33.36	-66.913
6	68	4	75840	9.795	-77.778
7	51	1	71880	22.28	-70.174
7	62	1	76120	14.13	-74.627
7	66	1	74500	13.39	-74.908
7	56	2	63870	22.74	-68.97
7	45	3	70980	24.66	-69.183
7	63	3	70470	24.36	-69.227
7	65	3	71530	12.91	-70.277
7	60	4	75720	6.044	-81.958
7	69	4	77520	5.663	-82.727
7	61	5	65610	2.895	-87.106
8	53	1	71660	31.7	-67.084
8	47	3	69100	33.71	-66.234
10	53	1	71660	9.946	-77.153
10	47	3	69100	14.66	-73.467
10	59	4	69830	34	-66.251
11	51	1	71880	15.8	-73.159
11	62	1	76120	22.32	-70.656
11	66	1	74500	12.76	-75.326
11	56	2	63870	13.17	-73.714
11	45	3	70980	9.352	-77.605
11	63	3	70470	26.92	-68.359
11	65	3	71530	13.98	-74.18
11	60	4	75720	68.51	-60.869
11	58	4	77310	37.76	-66.224
11	69	4	77520	36.4	-66.566
11	61	5	65610	4.821	-82.677
12	49	1	66350	7.968	-78.41
12	67	1	75710	7.094	-80.565
12	55	2	64520	7.679	-78.488
12	43	3	77900	9.818	-77.99
12	64	3	73940	8.252	-79.046
12	57	4	77690	29.15	-68.515
12	68	4	75840	28.08	-68.63

Table 6. Comparison of CW Data and HCB and Marx Test Results

Cable No.	Injection Point	Marx/ HCB	CW (dB)	I/Injection I (dB)
6	1	HCB	-63	-65.27
6	3	HCB	-73	-66.96
7	1	HCB	-60	-70.17
7	3	HCB	-73	-69.18
8	1	HCB	-56	-67.08
8	3	HCB	-73	-66.23
10	1	HCB	-73	-77.15
10	3	HCB	-76	-73.47
11	1	HCB	-76	-73.16
11	3	HCB	-74	-77.61
12	1	HCB	-74	-78.41
12	3	HCB	-83	-77.99
6	1	Marx	-108	-103.7
6	3	Marx	-100	-89.45
7	1	Marx	-120	-103.9
7	3	Marx	-120	-123.58
8	1	Marx	-120	-113.9
8	3	Marx	-120	-115.43
10	1	Marx	-120	-103.88
10	3	Marx	-120	-104.44
11	1	Marx	-108	-98.75
11	3	Marx	-120	-98.99
12	1	Marx	-120	-102.08
12	3	Marx	-120	-100.85

and HCB test results. The operating frequency of the Marx generator is approximately 100 kilohertz (kHz) and the operating frequency of the HCB is approximately 5 kHz. The purpose of this comparison is to demonstrate how the CW tests correlate with the high-level tests. This type of comparison was used to determine the improvement level for the new designs.

Table 3 compares the results of the CW testing per CTP-0051 with the results of CW testing per WTP-0238. This comparison shows an improvement in the high-frequency range of coupling. These results compare favorably with the

Marx generator response. The design modification reduced coupling by 12 dB to 36 dB, but CW testing in the 5-kHz region showed very little (0 dB to 10 dB) improvement.

Table 1 contains the results of the tests conducted with the external cables removed from the systems tunnel. Only injection Locations 1 and 3 were used. The results show some improvement in the coupling levels when the external cables are removed, but the improvement is very minor. This improvement may have been a function of the method employed in making the measurements or a function of the accuracy of the test equipment.

Marx testing at injection Location 1 for cables No. 7 and 11 was not performed because comparative data did not exist. An analysis performed by EMA in 1988 concluded that the dominant cause of cable coupling results from the magnetic fields generated from the current flowing on the RSRM case. The maximum coupling would be found in cables that run normal or parallel to the current flow. The results of this test help support this theory. The high-frequency components usually associated with the "E" field components were reduced substantially. The low-frequency component usually associated with the "H" field component was essentially unchanged following the modifications. In a memo from EMA to Thiokol, it was concluded that the dominant mode of coupling was the diffusion of the magnetic fields through the tunnel covers. The modifications that were tested would have little or no effect on this condition.

Two attachments were made directly to an external cable at Station 529 using the HCB. The cable itself was not damaged but the external shield was destroyed several inches on each side of the attachment point (Figures 10 and 11). The spot bonds that bond the external shields to the case nearest the attachment point were damaged (Figure 12). These two discharges are shown as shots No. 55 and 56. The resulting current detected on the cables inside the systems tunnel were not significantly different from the levels of the other attachment points.

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Figure 10. Damage to External Cable (with K5NA)

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Figure 11. Damage to External Cable (without K5NA)

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Figure 12. Spot Bond Damage

Bond strap testing was performed by injecting the current from the HCB onto the tunnel cover. Eight of the bond straps received an HCB and a CCB discharge concurrently. Additional shots using both banks had been planned, but, due to damage to the power supply and CCB controller, only the HCB was used for the remaining 10 shots. The decision to continue testing was made following a discussion with the USBI representative, an EMA representative, and the Thiokol Systems Integration engineer. This decision was made after the EMA representative demonstrated that the destructive force that would damage the bond straps would come from the HCB. It was also decided that the test levels should be increased unless multiple failures occurred.

There was a total of 19 bond straps tested, and of those 19, only two bond straps failed. Bond straps No. 1, 4, 6, 7, 9, 10, 11, and 13 survived action integrals of 2 million amp squared seconds and bond strap No. 5, 9, 10, and 11 survived action integrals exceeding 4 million amp squared seconds.

Bond straps No. 2 and 8 failed at action integrals of 2.19 million and 1.0 million amp squared seconds, respectively (Figures 13 and 14). Both bond straps were solid aluminum with notched edges, and they were both attached to the case with TRADUCT 2902. It is believed that bond strap No. 8 failed due to bond strap fatigue. This fatigue may have been caused by multiple strikes applied to the systems tunnel cover near bond strap No. 8. Failure of bond strap No. 2 is likely attributable to improper bond strap-to-case attachment and preparation.

Alternate bonding materials, TRADUCT 2902 and K5NA were used to attach the external bond straps to the RSRM case. Test data showed that TRADUCT 2902 performed better than ECCOBOND 56C.

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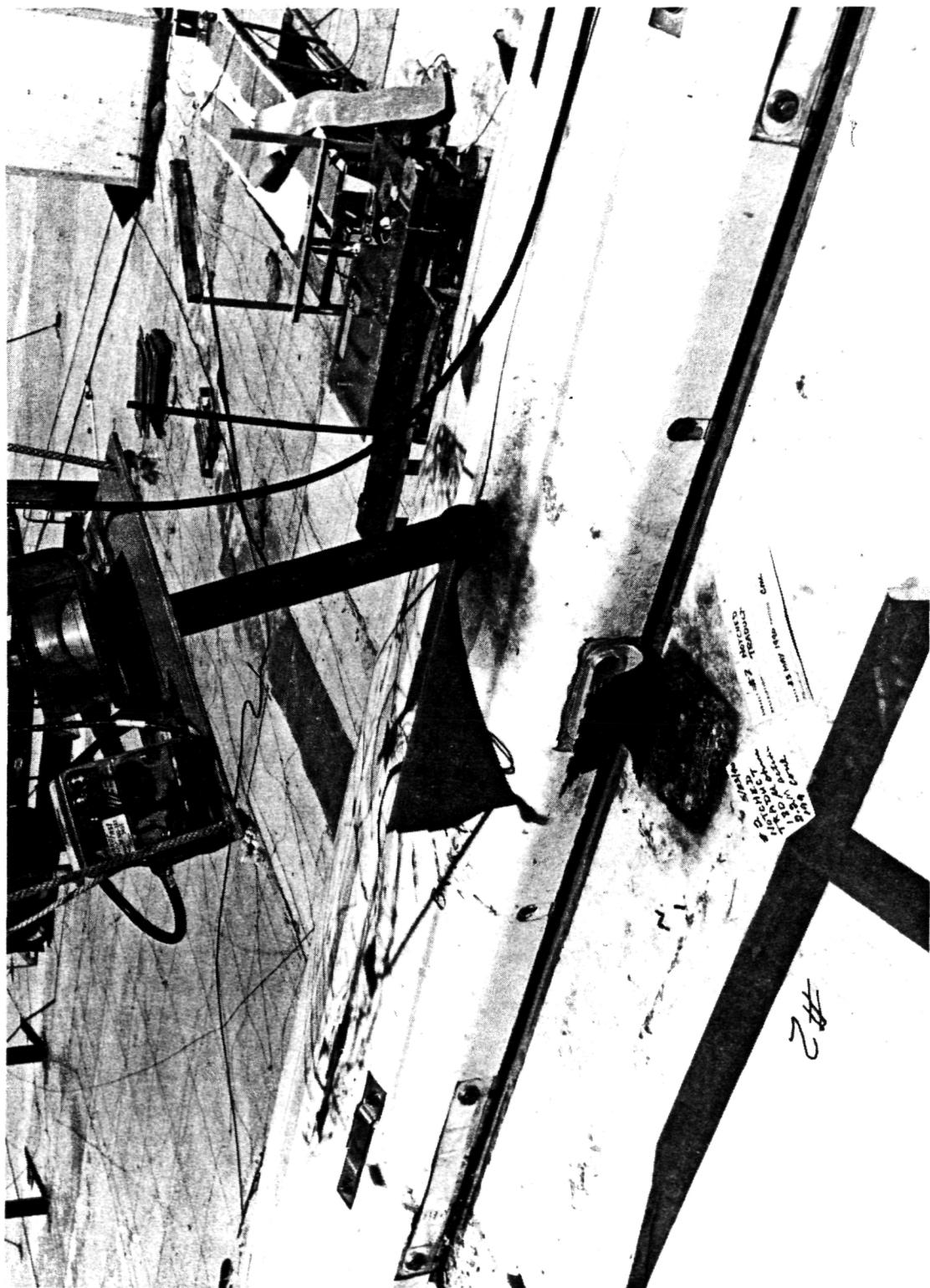


Figure 13. Failure of Bond Strap No. 2

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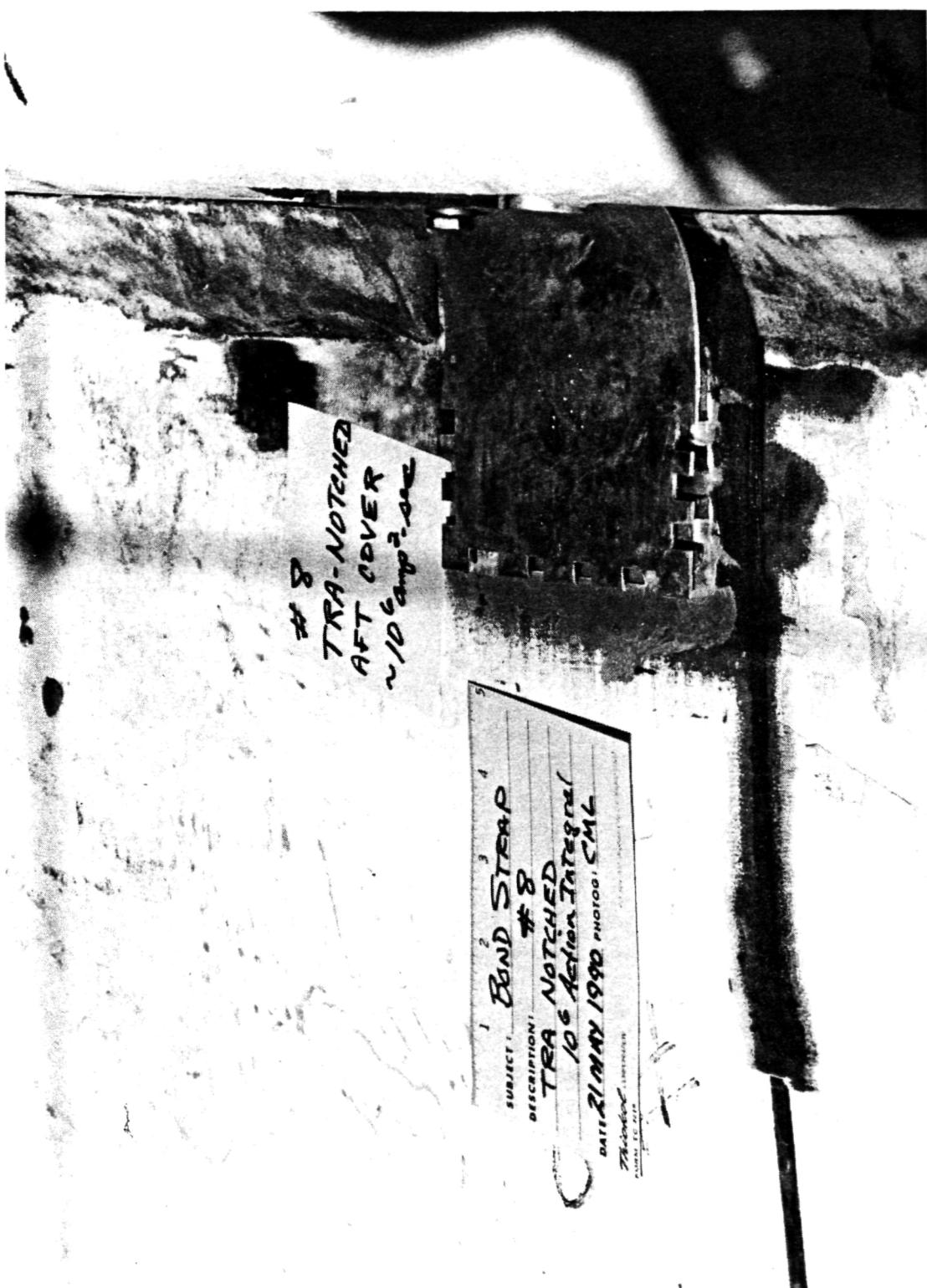


Figure 14. Failure of Bond Strap No. 8

6.5 CONCLUSIONS

Tables 1 and 3 through 6 demonstrate a fairly good correlation between the CW testing and the high-level testing and a good correlation between the previous testing and this series of tests. The results included in these tables are only for those situations where a direct comparison existed. Only the OF cables were monitored since they are of most interest to flight issues. The relation of these levels to flight motor expectation and previous testing is shown in Tables 1.5 and 1.6 of EMA-90-R-40. Testing showed that the a wider bond strap is more likely to withstand the currents from a lightning strike more than a narrow bond strap presently used for flight. The wider bond strap and better cover-to-cover bonding technique reduced the electric field components of coupling substantially. However, these modifications had little effect on the magnetic field component which is considered to be the main mode of coupling currents onto cables in the systems tunnel. Testing also showed that TRADUCT 2902 is a better conductive bonding material.

APPLICABLE DOCUMENTS

The latest revision of the following documents are applicable to the extent specified herein.

<u>Document No.</u>	<u>Title</u>
NSTS 07636	Lightning Protection Criteria Document
JSC 20007	Lightning Protection Verification Document
TWR-18364	Lightning Test Instrumentation List
STW4-3766	Adhesive, Electrically Conductive (TRADUCT 2902)
STW4-2874	Adhesive, Electrically Conductive (ECCOBOND 56C)
SYS-10-PLAN-004	SRB Systems Tunnel Lightning Coupling Re-Test Plan (USBI)
TWR-17796	Cable Coupling Lightning Transient Qualification Final Test Report
CTP-0051	Qualification Test Plan for the Cable Coupling Lightning Transient Test
NHB 5300.4	Safety, Reliability, Maintainability, and Quality Provisions for the Space Shuttle Program (1D-2)
ICD 3-44005	SRM-to-SRB Electrical and Instrumentation Subsystem
EMA-90-R-40	USBI Cable Coupling Responses
(no number)	Memo from Calvin Easterbrook, EMA, to Joe Godfrey, Thiokol Corporation, dated 20 June 1990, subject: Preliminary Report Letter Covering the SRM/SRB Design Enhancement Lightning Tests.

Military Standards

MIL-STD-45662	Calibration System Requirements
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Drawings

Drawing 7U77268	Lightning Test Article Follow-on Cable Tests
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Drawing 90001-0050	SRB Hardware Installation Lightning Test Article Number 2 (USBI)
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